Recycling and Biomass Influence on the Production-Based CO₂ Intensity Based on Circular Economy Concept

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Abstract

In a closed loop structure, the circular economy reflects a concept for converting material and energy wastes into capital for other purposes. The circular economy's key goal is to reduce energy and material waste. The best-case scenario will be to eliminate wastes and repurpose them, which is one of the key goals of the circular economy. The circular economy and sustainable development are inextricably linked. The framework reflects resource reuse and recycling in order to reduce waste and the use of biodegradable items that can be returned to the ecosystem after rejection. Many programs are being developed to incorporate the circular economy in order to apply the system's best practices. Recycling and reusing goods for the same or new items are the best practices for reducing waste and energy consumption. The main goal of the study was to analyze the effect of waste generation and recycling on production-based CO2 intensity based on circular economy concept. For such a purpose adaptive neuro fuzzy inference system (ANFIS) was implemented since the methodology is suitable for statistical investigation of strongly nonlinear data sample due to features of fuzzy logic system. Generated and recycled waste including biomass is the most influential factors for the production-based CO2 intensity based on circular economy concept. The obtained results could represent the best practices for implementation of circular economy concept.

Keywords: circular economy; waste; recycling; biomass; ANFIS.

1. Introduction

The circular economy is a framework for long-term sustainability that aims to reduce material and energy waste. Materials cycles are the central principle of the circular economy, which aims to minimize negative environmental effects, reduce energy consumption, and promote economic growth. The linear economy model has dominated industrial growth, resulting in pollution and the overuse of scarce natural resources. Reusing, remanufacturing, restoring, and updating goods or materials are all part of the circular economy. The circular economy in the energy sector is focused on renewable energy sources such as solar, wind, biomass, and waste-derived energy. One of the most critical circular economy principles is the use of biodegradable materials that can be returned to the atmosphere after being rejected, resulting in no waste.

In article [1] has been verified that the artificial neural network can be applied in different computational tasks in selected circular economy problems. Recycling and utilization of biomass constituents have been verified as the main factors in implementation of circular economy concept [2]. Circular economy presents a new way of economic growth based on effective usage of energy and material resources and environmental protection [3]. Results in article [4] have been shown that in circular economy domain was made important contributions to research but these contributions are heterogeneous with important differences and academic research does not fully align with the policy agenda. Hence there is need for more comprehensive investigation of circular economy parameters. It has been shown that the sustainable development in Industry 4.0 context could contribute to circular economy [5, 6]. Results in article [7] have been shown that there are large distinctions between different regions in China in circular economy development. Hence each region and each country have different factors and influences in circular economy development. Circular economy is based on different variables and factors and experts from different fields could make decisions based on the multiple attributed. This is not easy task and hence there is need to develop a decision-making model based on the multivariable group, which could facilitate decision and coordination between the different experts [8]. Results in article [9] have been indicated that the circular economy could improve economic development and ecological restoration as well. In article [10] has been shown important policy implications in periodical shift from the traditional linear economy to a circular economy. The impact of circular economy on economic growth has been investigated in article [11] and results have been shown that the GDP growth rate decreases significantly but the economic decline gradually recovers as time goes on. Results in article [12] have been shown a positive correlation between resources and environmental performance with the driving factors for circular transformation being mainly GDP and leading industries.

There are many initiatives in the works to incorporate circular economy best practices into the scheme. Recycling and reusing goods for the same or different items are the best practices. The main goal of the study was to analyze the effect of waste generation and recycling on production-based CO₂ intensity based on circular economy concept. For such a purpose adaptive neuro fuzzy inference system (ANFIS) [13] was implemented since the methodology is suitable for statistical investigation of strongly nonlinear data sample due to features of fuzzy logic system.

2. Methodology

2.1. Circular economy concept

79 The circular economy is an economic mechanism whose primary goal is to eradicate waste
80 and make continuous use of resources. In order to build a closed loop structure, the key tasks in
81 the circular economy are to reuse, restore, remanufacture, and recycle. The circular economy's key
82 aim is to reduce resource inputs and waste, as well as pollution and carbon emissions. The circular
83 economy's second aim is to keep goods, facilities, and infrastructure in use for longer periods of
84 time. The circular economy principle is illustrated in Figure 1. Other processes should use maternal
85 and oil wastes as inputs. As a result, in order to generate regenerative resources and remove waste
86 materials and energy, a regenerative approach is needed. The circular economy has five key
87 measures that result in a closed loop structure. (Figure 2).

Figure 1: Circular economy concept

Figure 2: Closed loop system of circular economy

2.2. Scottish Household waste

The used dataset was generated between 2017 and 2019 as summary of household waste data generated in Scotland and managed by or on behalf of Scottish local authorities. The carbon impact is a measure of the whole-life carbon impacts of waste, from resource extraction and manufacturing emissions, right through to waste management emissions. The carbon impact of household waste generated and managed as tonnes of carbon dioxide equivalent (TCO₂e). All of the data in this report is available in the Household Waste Discover Data tool on Scotland's Environment website (<https://www.environment.gov.scot/>). Annual household waste summary data tables are also available to download in Excel format on SEPA's web site (<https://www.sepa.org.uk/environment/waste/waste-data/waste-data-reporting/household-waste-data/>). Tables 1 shows the used dataset with 4 inputs and one output. The first input represents the total generated waste in in tonnes per person. The second input is recycled waste in tonnes per person. Waste recycled includes waste reused, recycled or composted. The third input represents wastes of other division from landfill in tonnes per person. Other diversion from landfill is waste material not recycled or landfilled. This includes net waste incinerated, incinerator outputs recycled, and organic material recycled that does not meet quality standards. The fourth input represent the waste landfilled. The output represents the Carbon impacts of Scottish household waste in TCO₂e. Data was submitted by all 32 Scottish local authorities using the web-based reporting tool WasteDataFlow.

Table 1: Scottish Household waste generated and managed per person between 2017-2019

Local Authority	Year	Generated (tonnes per person)	Recycled (tonnes per person)	Other diversion from landfill (tonnes per person)	Landfilled (tonnes per person)	Carbon Impact (TCO2e per person)
Aberdeen City	2017	0.38	0.17	0.08	0.14	0.87
Aberdeenshire	2017	0.49	0.21	0.01	0.27	1.24
Angus	2017	0.48	0.27	0.10	0.11	1.00
Argyll and Bute	2017	0.58	0.23	0.08	0.27	1.46
City of Edinburgh	2017	0.39	0.16	0.01	0.22	0.99
Clackmannanshire	2017	0.53	0.31	0.06	0.16	1.08
Dumfries and Galloway	2017	0.51	0.14	0.16	0.21	1.47
Dundee City	2017	0.43	0.15	0.25	0.03	1.04
East Ayrshire	2017	0.46	0.24	0.04	0.17	0.98
East Dunbartonshire	2017	0.52	0.25	0.06	0.21	1.21
East Lothian	2017	0.48	0.26	0.00	0.22	1.07
East Renfrewshire	2017	0.50	0.34	0.02	0.15	1.01
Falkirk	2017	0.47	0.26	0.05	0.15	0.94
Fife	2017	0.48	0.26	0.03	0.19	0.94
Glasgow City	2017	0.36	0.10	0.02	0.24	1.10
Highland	2017	0.55	0.24	0.01	0.31	1.37
Inverclyde	2017	0.35	0.20	0.02	0.13	0.72
Midlothian	2017	0.47	0.24	0.02	0.21	1.09
Moray	2017	0.53	0.31	0.00	0.23	1.02
Na h-Eileanan Siar	2017	0.54	0.13	0.06	0.35	1.43
North Ayrshire	2017	0.46	0.26	0.01	0.19	1.01
North Lanarkshire	2017	0.46	0.18	0.02	0.26	1.20
Orkney Islands	2017	0.49	0.09	0.22	0.15	1.32
Perth and Kinross	2017	0.49	0.28	0.03	0.19	0.93
Renfrewshire	2017	0.47	0.23	0.11	0.13	1.11
Scottish Borders	2017	0.46	0.19	0.01	0.27	1.17
Shetland Islands	2017	0.42	0.03	0.29	0.09	1.39
South Ayrshire	2017	0.50	0.28	0.05	0.18	1.12
South Lanarkshire	2017	0.48	0.23	0.00	0.25	1.17
Stirling	2017	0.43	0.24	0.07	0.13	0.90
West Dunbartonshire	2017	0.49	0.23	0.04	0.21	1.17
West Lothian	2017	0.39	0.24	0.04	0.11	0.80
Aberdeen City	2018	0.38	0.18	0.12	0.08	0.87
Aberdeenshire	2018	0.46	0.20	0.01	0.25	1.18
Angus	2018	0.47	0.26	0.19	0.02	0.97
Argyll and Bute	2018	0.56	0.21	0.09	0.26	1.38
City of Edinburgh	2018	0.37	0.14	0.03	0.19	0.95
Clackmannanshire	2018	0.51	0.29	0.01	0.21	1.04
Dumfries and Galloway	2018	0.53	0.15	0.15	0.24	1.53
Dundee City	2018	0.41	0.15	0.23	0.03	1.00
East Ayrshire	2018	0.44	0.23	0.04	0.17	0.97
East Dunbartonshire	2018	0.48	0.26	0.09	0.12	1.03
East Lothian	2018	0.47	0.25	0.02	0.20	1.05
East Renfrewshire	2018	0.46	0.31	0.01	0.14	0.94
Falkirk	2018	0.43	0.22	0.02	0.19	0.97
Fife	2018	0.45	0.23	0.03	0.19	0.91
Glasgow City	2018	0.39	0.10	0.03	0.27	1.17
Highland	2018	0.54	0.23	0.03	0.28	1.35
Inverclyde	2018	0.36	0.20	0.02	0.14	0.74
Midlothian	2018	0.46	0.27	0.06	0.13	1.01
Moray	2018	0.50	0.29	0.00	0.21	0.96
Na h-Eileanan Siar	2018	0.53	0.12	0.07	0.35	1.41
North Ayrshire	2018	0.45	0.25	0.05	0.16	1.04
North Lanarkshire	2018	0.43	0.19	0.06	0.18	1.04
Orkney Islands	2018	0.46	0.10	0.22	0.12	1.22
Perth and Kinross	2018	0.47	0.25	0.03	0.20	0.93
Renfrewshire	2018	0.46	0.22	0.14	0.10	1.07
Scottish Borders	2018	0.46	0.18	0.01	0.27	1.16

Shetland Islands	2018	0.42	0.04	0.28	0.09	1.35
South Ayrshire	2018	0.50	0.26	0.06	0.18	1.11
South Lanarkshire	2018	0.47	0.21	0.04	0.23	1.13
Stirling	2018	0.44	0.24	0.00	0.20	0.93
West Dunbartonshire	2018	0.47	0.20	0.05	0.22	1.15
West Lothian	2018	0.41	0.27	0.04	0.10	0.83
Aberdeen City	2019	0.37	0.18	0.12	0.07	0.79
Aberdeenshire	2019	0.47	0.21	0.01	0.25	1.19
Angus	2019	0.45	0.27	0.16	0.02	0.87
Argyll and Bute	2019	0.55	0.21	0.08	0.25	1.37
City of Edinburgh	2019	0.37	0.14	0.21	0.02	0.90
Clackmannanshire	2019	0.49	0.27	0.00	0.22	1.03
Dumfries and Galloway	2019	0.52	0.15	0.23	0.13	1.41
Dundee City	2019	0.44	0.17	0.24	0.03	1.00
East Ayrshire	2019	0.45	0.24	0.04	0.17	0.98
East Dunbartonshire	2019	0.49	0.27	0.12	0.09	1.02
East Lothian	2019	0.47	0.26	0.14	0.07	0.99
East Renfrewshire	2019	0.51	0.34	0.01	0.15	0.99
Falkirk	2019	0.44	0.23	0.01	0.19	0.96
Fife	2019	0.47	0.21	0.05	0.21	1.04
Glasgow City	2019	0.40	0.10	0.11	0.20	1.18
Highland	2019	0.53	0.22	0.04	0.27	1.26
Inverclyde	2019	0.36	0.19	0.02	0.14	0.75
Midlothian	2019	0.44	0.22	0.17	0.05	0.99
Moray	2019	0.49	0.29	0.00	0.20	0.92
Na h-Eileanan Siar	2019	0.51	0.11	0.07	0.34	1.37
North Ayrshire	2019	0.45	0.25	0.07	0.12	0.99
North Lanarkshire	2019	0.44	0.18	0.17	0.09	1.06
Orkney Islands	2019	0.47	0.09	0.23	0.12	1.21
Perth and Kinross	2019	0.49	0.26	0.03	0.20	0.93
Renfrewshire	2019	0.45	0.24	0.14	0.08	1.01
Scottish Borders	2019	0.45	0.22	0.10	0.13	1.07
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South Ayrshire	2019	0.47	0.27	0.05	0.15	0.97
South Lanarkshire	2019	0.46	0.21	0.13	0.12	1.05
Stirling	2019	0.45	0.25	0.00	0.20	0.92
West Dunbartonshire	2019	0.45	0.20	0.05	0.20	1.07
West Lothian	2019	0.42	0.25	0.11	0.06	0.87

Carbon Impact is a measure of the whole-life carbon impacts of waste, from resource extraction and manufacturing emissions, right through to waste management emissions, regardless of where in the world these impacts occur. The carbon impact of waste was developed by Zero Waste Scotland (<https://www.zerowastescotland.org.uk/content/whatcarbon-metric>).

Household waste includes:

- household waste treated by incineration, including any incinerator bottom ash and metals from bottom ash that are diverted from landfill,
- weight loss that occurs during the composting/digestion of waste to PAS 100/110 and non PAS 100/110 compost/digestate where the output is landfilled,
- Compost like output (CLO) that is not landfilled,
- weight loss that occurs during mechanical and biological treatment processes,

Recycling rate is waste recycled as a percentage of all waste generated. Note that total waste generated does not equal total waste managed due to stockpiled waste, which is counted in the generation figures and will be included in the managed figures in the year it is sent to final management.

TCO_{2e} is tonnes of carbon dioxide equivalent, which is a measure that allows the comparison of greenhouse gases relative to one unit of CO₂. Waste composted is waste recycled by biological treatment through composting at a composting plant or through digestion at an anaerobic digestion facility. Waste generated is waste collected by or on behalf of local authorities that is managed within the relevant reporting year. This might include treated waste stockpiled prior to final management.

Waste landfilled includes all household waste that is disposed of at a landfill site instead of being recycled or diverted from landfill through other methods. It also includes incinerator ash that is landfilled, plus any recycling and composting rejects that occur during collection, sorting or further treatment that go to landfill.

Waste managed includes all wastes recycled, diverted from landfill and landfilled within the relevant reporting year. This includes stockpiled waste from a previous year sent to final management but excludes treated waste stockpiled prior to final management.

Waste recycled includes recyclable materials that have been recycled or reused and also biodegradable materials that have been composted or digested. The amount of waste recycled, reused and composted is that accepted by the reprocessor facility. As such it excludes any recycling rejects that occur during collection, sorting or further treatment.

2.3. OECD Green Growth database for CO₂ intensity

In this study was used energy and non-energy material productivity parameters for CO₂ intensity evaluation. Non-energy material productivity parameters are based on the waste materials and recycling. Energy productivity parameters represent energy consumption. In this study are used OECD Green Growth database [14] which contains selected indicators for monitoring progress towards green growth to support policy making and inform the public at large. The database synthesizes data and indicators across a wide range of domains. The database covers OECD members.

The indicators have been selected according to well-specified criteria and embedded in a conceptual framework. The main goal is to capture the main features of green growth based on environmental and resource productivity. There is need to indicate whether economic growth is becoming greener with more efficient use of natural capital and to capture aspects of production which are rarely quantified in economic models and accounting frameworks. Two sets of data are created. The first set represent energy productivity parameters (Table 2). The second set represent non-energy productivity parameters (Table 3).

Table 2: OECD Energy productivity parameters [14]

Energy productivity, GDP per unit of TPES	Energy intensity, TPES per capita	Total primary energy supply, index 2000=100	Total primary energy supply	Renewable energy supply, % total energy supply	Renewable electricity, % total electricity generation	Energy consumption in agriculture, % total energy consumption	Energy consumption in services, % total energy consumption	Energy consumption in industry, % total energy consumption	Energy consumption in transport, % total energy consumption	Energy consumption in other sectors, % total energy consumption	Production-based CO ₂ intensity, energy-related CO ₂ per capita, Tonnes
8826.367	3.254377	95.44046	1678.353	6.420461	18.5517	2.950462	10.23068	26.22146	24.68238	35.91433	7.46
11707.61	3.179969	100.7703	1772.08	11.27353	24.70799	2.640972	12.62459	23.98399	26.97872	33.77164	6.62
11731.95	3.158605	100.5814	1768.758	12.47474	27.91644	2.553398	13.01538	23.60345	26.28076	34.54701	6.56

11932.29	3.120545	99.84254	1755.765	13.12106	30.1717	2.571397	13.16731	23.33632	26.25779	34.66735	6.39
12655.89	2.98967	96.10636	1690.063	13.63062	31.46343	2.659827	12.78105	23.94561	27.71869	32.89499	6.06
12795.84	3.022118	97.60636	1716.441	14.06999	33.04113	2.499092	13.14044	23.46823	27.79351	33.09873	6.13
12954.69	3.032611	98.40902	1730.556	14.2445	33.33186	2.525502	13.15796	23.15053	27.98008	33.18602	6.11
13121.2	3.07226	100.1639	1761.417	14.40108	33.45408	2.541875	13.04277	23.55828	27.99207	32.86501	6.16
5352.338	5.581285	83.84415	2288.226	6.961026	19.09514	1.364847	11.51985	23.34249	36.26098	27.51171	8.32
5605.401	5.675304	90.83206	2478.936	7.118982	18.77071	1.367863	11.82618	21.50333	36.83042	28.4722	9.27
6287.054	5.854374	100	2729.142	6.447741	16.0582	1.206874	11.83079	22.90521	36.79903	27.2582	9.81
6868.174	5.750032	103.6581	2828.978	6.443316	16.10363	1.677225	12.01204	19.51234	38.75154	28.04681	10.09
7550.711	5.230707	99.57514	2717.547	7.346258	17.24032	1.76541	12.68244	19.37154	38.73235	27.44826	10.21
7741.915	5.155612	99.12372	2705.227	7.864479	19.41638	1.785822	12.83744	19.53984	38.62576	27.21119	10.53
8019.06	5.050881	98.03568	2675.533	8.200684	19.32087	1.74518	12.47072	19.91062	39.01956	26.85392	10.72
8016.53	5.104189	99.98215	2728.655	8.619265	20.04105	1.694568	12.69241	19.46404	39.00652	27.14256	10.65
8147.765	5.107526	100.9511	2755.1	8.63221	20.45455	1.636462	12.89735	19.21322	38.47406	27.77891	10.31
8462.196	5.016077	100.032	2730.016	8.595517	20.66553	1.716439	12.72969	19.21101	39.69491	26.64827	10.24
8666.114	4.941216	99.41963	2713.303	8.8508	22.08114	1.696488	12.72559	19.18978	40.03992	26.34816	10.24
8882.95	4.889446	99.24834	2708.628	9.24793	24.1985	1.72511	12.68393	19.04909	40.12773	26.41415	10.20
8194.264	3.339897	75.55217	642.031	3.976755	12.39039	2.340472	10.90509	35.23991	26.29814	25.21638	13.52
7858.75	3.831093	89.53382	760.845	3.472061	10.14154	2.17794	13.10679	32.03857	27.34161	25.3347	13.50
7839.162	4.171752	100	849.785	3.385445	9.018647	2.17077	13.70079	30.7091	26.7374	26.68176	14.36
8403.907	4.24036	103.7258	881.446	3.501632	8.268871	2.109931	14.69172	29.19155	26.30231	27.70432	13.74
8629.543	4.336745	108.1701	919.213	3.868527	8.572367	1.956162	14.30385	28.65298	25.77892	29.30757	12.41
9007.837	4.196933	105.0629	892.809	4.062795	9.214039	1.874756	14.22723	29.20513	25.48949	29.20357	11.94
9250.417	4.149241	104.2317	885.745	3.945718	8.798679	1.893719	13.86529	28.82656	25.52133	29.89328	11.40
9462.185	4.140055	104.3403	886.668	4.266535	9.726371	1.834807	14.17982	29.13196	25.36626	29.48715	11.58
9710.062	4.078918	103.1002	876.13	4.711858	10.89627	1.772406	14.17716	29.09455	25.42591	29.5298	11.46
9913.527	4.059661	102.871	874.182	4.957206	11.84383	1.870634	14.1357	28.23516	25.92617	29.83199	11.16
10010.63	4.071079	103.373	878.448	4.952598	12.22848	1.922751	14.08912	27.81522	25.98659	30.18666	10.91
10204.06	4.090365	104.0321	884.049	5.280137	13.31454	1.847376	13.94631	27.49142	25.78605	30.92867	10.68

Table 3: OECD Non-energy material productivity parameters [14]

Non-energy material productivity, GDP per unit of DMC	Biomass, % of DMC	Non-metallic minerals, % of DMC	Metals, % of DMC	Municipal waste generated; kg per capita	Production-based CO2 intensity, energy-related CO2 per capita, Tonnes
0	33.33333	33.33333	33.33333	477.872	7.46
3.403811	31.01805	63.46789	5.514061	499.218	6.62
3.765492	33.37396	60.98759	5.638452	487.942	6.56
3.857792	34.02959	59.18972	6.780695	481.19	6.39
3.812986	35.26351	58.32495	6.41154	480.822	6.06
3.986153	33.89724	58.90404	7.198723	482.499	6.13
4.043387	34.35774	58.74871	6.893549	494.537	6.11
3.992864	34.29899	59.33814	6.362866	493.16	6.16
1.886461	23.30155	57.35181	19.34664	609.885	8.32
1.982073	21.98267	57.24782	20.76951	616.023	9.27
2.063529	22.77075	57.10828	20.12097	640.808	9.81
2.217392	22.85453	59.90219	17.24328	645.143	10.09
2.874452	28.32773	50.72296	20.94931	620.523	10.21
2.92041	28.3162	50.46878	21.21502	617.748	10.53
3.228215	29.64258	45.52305	24.83437	616.236	10.72
3.111924	30.84143	44.54292	24.61565	617.478	10.65
3.242061	31.58285	43.15933	25.25782	619.287	10.31
3.37943	32.44012	41.88441	25.67547	622.35	10.24
3.48951	33.20387	40.65423	26.1419	617.691	10.24
3.62182	33.97746	39.41026	26.61228	614.56	10.20
2.375676	19.43443	62.07285	18.49272	423.211	13.52
2.465624	20.05789	62.51141	17.43069	446.842	13.50
2.662974	20.64682	59.0311	20.32209	449.778	14.36
3.100619	21.48204	57.75063	20.76732	434.163	13.74
3.657303	22.1197	55.03258	22.84772	394.826	12.41
3.688337	22.42532	54.31113	23.26355	393.49	11.94
4.178116	25.52284	49.18826	25.28891	392.397	11.40
4.28764	25.12926	48.57531	26.29542	390.61	11.58
4.3635	25.54854	47.99104	26.46042	391.202	11.46
4.528671	25.97681	47.02766	26.99553	393.887	11.16
4.687572	26.46947	45.95464	27.5759	393.292	10.91
4.855577	26.69905	45.41676	27.88419	393.666	10.68

Energy productivity is calculated as GDP per unit of Total Primary Energy Supply (TPES). It reflects, at least partly, efforts to improve energy efficiency and to reduce carbon and other atmospheric emissions. Together with energy intensity, these indicators also reflect structural and climatic factors. TPES comprises production + imports - exports - international marine bunkers - international aviation bunkers ± stock changes. Energy intensity is calculated as TPES per capita. Total primary energy supply (TPES) is expressed in million tons of oil equivalent. TPES is also expressed as an index with values in 2000 normalized to equal 100. Renewable energy supply is calculated as a share of renewable sources in TPES (expressed as percentage). Renewables include hydro, geothermal, solar (thermal and PV), wind and tide/wave/ocean energy, as well as combustible renewables (solid biomass, liquid biomass, biogas) and waste (renewable municipal

waste). Renewable electricity is calculated as a share of renewables in electricity production (%). Energy consumption in agriculture is expressed as a share of total energy consumption (%). Energy consumption in agriculture includes deliveries to users classified as agriculture, hunting and forestry by the International Standard Industrial Classification (ISIC). Therefore, it includes energy consumed by such users whether for traction (excluding agricultural highway use), power or heating (agricultural and domestic). Energy consumption in services is expressed as a share of total energy consumption (%). Energy consumption in services includes both commercial and public services. Energy consumption in transport is expressed as a share of total energy consumption (%). Energy consumption in transport covers all transport activity (in mobile engines) regardless of the economic sector to which it is contributing. Energy consumption in industry is expressed as a share of total energy consumption (%). Energy consumption in industry includes the following sub-sectors: iron and steel, chemical and petrochemical, non-ferrous metals, non-metallic minerals, transport equipment, machinery, mining and quarrying, food and tobacco, paper, pulp and print, wood and wood products, construction, textile and leather together with any manufacturing industry not included above. Energy consumption in other sectors is expressed as a share of total energy consumption (%). Energy consumption in other sectors includes residential consumption and all fuel use not elsewhere specified.

Non-energy material productivity is calculated as GDP generated per unit of materials consumed. Domestic Material Consumption (DMC) refers to the apparent consumption of materials; it is calculated as the sum of domestic consumption of biomass for food and feed, construction minerals, industrial minerals, metals and wood. Consumption of Biomass is expressed as a percentage of DMC. Biomass materials include biomass for food and wood. Food materials include crops (e.g. cereals, roots, sugar and oil bearing crops, fruits, vegetables), fodder crops (including grazing), wild animals (essentially marine catches), small amounts of non-edible biomass (e.g. fibres, rubber), and related products including livestock. Wood includes harvested wood and traded products made of wood (e.g. paper, furniture, etc.). Total domestic material consumption refers to the apparent consumption of materials; it is calculated as the sum of domestic consumption of biomass for food and feed, construction minerals, industrial minerals, metals and wood. Consumption of non-metallic materials is expressed as a percentage of Domestic Material Consumption (DMC). Non-metallic minerals include construction and industrial minerals. Construction minerals include primary (e.g. sand, gravel, stones, limestone, excavated soil if used) or processed (e.g. glass, cement, concrete) minerals. Industrial minerals include primary or processed non-metallic minerals (e.g. salts, arsenic, potash, phosphate rocks, sulphates and asbestos). Consumption of metals is expressed as a percentage of DMC. Metals include metal ores, metals and products made of metals. Municipal waste generated is expressed in kg per person. Municipal waste is waste collected by or on behalf of municipalities. It includes household waste originating from households (i.e. waste generated by the domestic activity of households) and similar waste from small commercial activities, office buildings, institutions such as schools and government buildings, and small businesses that treat or dispose of waste at the same facilities used for municipally collected waste.

Production-based CO2 intensity is calculated as CO2 emissions per capita (tonnes/person). Included are CO2 emissions from combustion of coal, oil, natural gas and other fuels. The estimates of CO2 emissions are obtained from the IEA's database of CO2 emissions from fuel combustion.

2.4. ANFIS methodology

The ANFIS network has five layers, each of which performs a different operation during the training process (Figure 3). The ANFIS network's key core is the fuzzy inference framework (FIS). The first layer takes in input signals and uses membership functions to translate them to fuzzy values. The bell-shaped membership function is used in this study because it has the best capability for nonlinear data regression.

Figure 3: ANFIS structure

The following is a description of bell-shaped membership functions::

$$\mu(x) = bell(x; a_i, b_i, c_i) = \frac{1}{1 + \left[\left(\frac{x - c_i}{a_i} \right)^2 \right]^{b_i}} \quad (1)$$

where $\{a_i, b_i, c_i\}$ is the parameters set and x is input.

By multiplying the fuzzy singlas from the first layer, the second layer provides the rule's firing power. Many of the signals from the second layer are normalized in the third layer. The fourth layer is responsible for rule inference. The final layers summed all of the signals and provided a crisp output value.

ANFIS methodology was implemented in MATLAB software for the selection procedure. During selection procedure non-relevant parameters could be removed. Parameters with small relevance do not have high impact on the output. The dataset is partitioned into a training set (trn_data) and a checking set (chk_data). The function "exhsrch" represents exhaustive search procedure within the given inputs.

3. Results

3.1. Accuracy indices

The following are the results of the proposed model as root mean square error (RMSE), coefficient of determination (R²), and Pearson coefficient (r):

1) RMSE

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}}, \quad (2)$$

2) Pearson correlation coefficient (r)

$$r = \frac{n \left(\sum_{i=1}^n O_i \cdot P_i \right) - \left(\sum_{i=1}^n O_i \right) \cdot \left(\sum_{i=1}^n P_i \right)}{\sqrt{\left(n \sum_{i=1}^n O_i^2 - \left(\sum_{i=1}^n O_i \right)^2 \right) \cdot \left(n \sum_{i=1}^n P_i^2 - \left(\sum_{i=1}^n P_i \right)^2 \right)}} \quad (3)$$

3) Coefficient of determination (R²)

$$R^2 = \frac{\left[\sum_{i=1}^n (O_i - \bar{O}_i) \cdot (P_i - \bar{P}_i) \right]^2}{\sum_{i=1}^n (O_i - \bar{O}_i) \cdot \sum_{i=1}^n (P_i - \bar{P}_i)} \quad (4)$$

where P_i and O_i are known as the experimental and forecast values, respectively, and n is the total number of checking data.

3.2. ANFIS results

In the first stage ANFIS network is trained with data section in Table 1 where there are four input variables and the output is TCO_{2e}. The main goal is to determine RMS errors of each single parameter from the Table 1 based on the TCO_{2e} prediction. Figure 4 shows the RMSE errors of the single parameters. One can note the generated waste has the smallest RMS error hence the strongest relevance in regard to the TCO_{2e} prediction. There are two RMS errors, for training (trn) and for checking (chk) of the ANFIS models. 50% data were used as training data while remaining 50% data were used as checking data. Each of the ANFIS model is trained with one epoch in order to determine the parameters' relevance to the TCO_{2e}. Based on the comparison of

the training and checking errors there is no overfitting in the ANFIS models since the training and checking errors are comparable. Figure 5 shows the optimal combination of single input and single output for the best TCO2e prediction.

Figure 4: RMS errors of the single parameters for Scottish Household waste

Figure 5: Optimal combination with one input in circular economy based on carbon emission impact

Table 4 shows the RMS errors of the single parameter for OECD database. Based on the results energy intensity has the highest impact on the CO2 intensity in the OECD members.

Table 4: RMS errors of the single parameters for OECD database

Energy productivity --> trn=1.1675, chk=0.9051
Energy intensity --> trn=0.2890, chk=0.2700
Total primary energy supply, index --> trn=2.2897, chk=2.2158
Total primary energy supply --> trn=1.4048, chk=1.1236
Renewable energy supply --> trn=1.4174, chk=0.8156
Renewable electricity --> trn=1.5567, chk=1.1026
Energy consumption in agriculture --> trn=0.7198, chk=0.8032
Energy consumption in services --> trn=1.7271, chk=1.7456
Energy consumption in industry --> trn=2.1346, chk=1.7229
Energy consumption in transport --> trn=1.2553, chk=1.1864
Energy consumption in other sectors --> trn=1.0176, chk=0.9700
Non-energy material productivity --> trn=1.9626, chk=1.8932
Biomass --> trn=1.6200, chk=1.9191
Non-metallic minerals --> trn=2.0336, chk=2.1524
Metals --> trn=1.2922, chk=1.1244
Municipal waste generated --> trn=0.8411, chk=0.7793

Figure 6 shows the RMS errors of the combinations of two parameters for Scottish Household waste. One can note the combination of generated and recycled wastes is the optimal combination for the TCO2e prediction. Figure 7 shows the optimal combination with two inputs and one output for the TCO2e prediction.

Figure 6: RMS errors of the combinations of two parameters for Scottish Household waste

Figure 7: Optimal combination with one input in circular economy based on carbon emission impact

Based on the results for the OECD database energy intensity and biomass consumption is the optimal combination ($\text{trn}=0.0777$, $\text{chk}=0.2759$) of two parameters with the highest impact on the CO₂ intensity in the OECD members. Therefore, biomass has the very high carbon impact and it has to be recycled and reused in circular economy.

Three selected parameters are extracted and new ANFIS model is generated and trained with 100 epochs. Figure 8 shows the ANFIS prediction of TCO₂e index based on two selected combinations. The all data are used for ANFIS training and checking as well. In other words, ANFIS was trained with all data and then checking against the same data. There is high prediction accuracy based on three statistical indicators ($r=0.977134$, $\text{RMSE}=0.037568$, $R^2=0.9548$).

Figure 8: ANFIS prediction of TCO2e based on the selected input combinations for Scottish Household waste

Figure 9 shows the ANFIS prediction of TCO2e index based on two selected combinations. The all data are used for ANFIS training and checking as well. In other words, ANFIS was trained with all data and then checking against the same data. There is high prediction accuracy based on three statistical indicators ($r=0.999966$, $RMSE=0.019732$, $R^2=0.9999$).

Figure 9: ANFIS prediction of production-based CO2 intensity based on the selected input combinations for OECD members

4. Conclusion

Since ecological and environmental sustainability are at the forefront of the economy, the circular economy is the economy for the future. The circular economy's central concept is human life's long-term viability. The circular economy may offer a way to overcome the current production and consumption model, which is limited in terms of energy resources. This economy is focused on a closed-loop system in which the primary energy and material resources are urban and industrial wastes.

The main goal of the study was to analyze the effect of waste generation and recycling on production-based CO₂ intensity based on circular economy concept. For such a purpose adaptive neuro fuzzy inference system (ANFIS) was implemented since the methodology is suitable for statistical investigation of strongly nonlinear data sample. Generated and recycled waste including biomass is the most influential factors for the production-based CO₂ intensity based on circular economy concept. The main concluding remarks could be summed as follows:

- Generated waste has high impact on the carbon dioxide emission,
- Biomass consumption has the high impact on the carbon dioxide emission,

References

- [1] Sakiewicz, P., Piotrowski, K., & Kalisz, S. (2020). Neural network prediction of parameters of biomass ashes, reused within the circular economy frame. *Renewable Energy*, 162, 743-753.
- [2] Shanmugam, V., Mensah, R. A., Försth, M., Sas, G., Restás, Á., Addy, C., ... & Ramakrishna, S. (2021). Circular economy in biocomposite development: State-of-the-art, challenges and emerging trends. *Composites Part C: Open Access*, 100138.
- [3] Tang, J., Tong, M., Sun, Y., Du, J., & Liu, N. (2020). A spatio-temporal perspective of China's industrial circular economy development. *Science of the total environment*, 706, 135754.
- [4] Belmonte-Ureña, L. J., Plaza-Úbeda, J. A., Vazquez-Brust, D., & Yakovleva, N. (2021). Circular economy, degrowth and green growth as pathways for research on sustainable development goals: A global analysis and future agenda. *Ecological Economics*, 185, 107050.
- [5] Sakiewicz, P., Piotrowski, K., & Kalisz, S. (2020). Neural network prediction of parameters of biomass ashes, reused within the circular economy frame. *Renewable Energy*, 162, 743-753.
- [6] Zhou, X., Song, M., & Cui, L. (2020). Driving force for China's economic development under Industry 4.0 and circular economy: Technological innovation or structural change?. *Journal of Cleaner Production*, 271, 122680.
- [7] Fan, Y., & Fang, C. (2020). Circular economy development in China-current situation, evaluation and policy implications. *Environmental Impact Assessment Review*, 84, 106441.

- [8] Tang, M., & Liao, H. (2021). Multi-attribute large-scale group decision making with data mining and subgroup leaders: An application to the development of the circular economy. *Technological Forecasting and Social Change*, 167, 120719.
- [9] Cheng, H., Dong, S., Li, F., Yang, Y., Li, Y., & Li, Z. (2019). A circular economy system for breaking the development dilemma of 'ecological Fragility–Economic poverty' vicious circle: A CEEPS-SD analysis. *Journal of Cleaner Production*, 212, 381-392.
- [10] Magazzino, C., Mele, M., Schneider, N., & Sarkodie, S. A. (2021). Waste generation, wealth and GHG emissions from the waste sector: Is Denmark on the path towards circular economy?. *Science of the Total Environment*, 755, 142510.
- [11] Chen, Z., Chen, S., Liu, C., Nguyen, L. T., & Hasan, A. (2020). The effects of circular economy on economic growth: A quasi-natural experiment in China. *Journal of Cleaner Production*, 271, 122558.
- [12] Wang, N., Guo, J., Zhang, X., Zhang, J., Li, Z., Meng, F., ... & Ren, X. (2021). The circular economy transformation in industrial parks: Theoretical reframing of the resource and environment matrix. *Resources, Conservation and Recycling*, 167, 105251.
- [13] Jang, J. S. (1993). ANFIS: adaptive-network-based fuzzy inference system. *IEEE transactions on systems, man, and cybernetics*, 23(3), 665-685.
- [14] https://stats.oecd.org/Index.aspx?DataSetCode=GREEN_GROWTH